Journal of Civil Engineering and Materials Application
Journal home page: http://jcema.com

Received: 08 December 2025 • Revised: 20 January 2026 • Accepted: 30 February 2026

Research

doi: 10.22034/jcema.2026.575450.1195

Sustainable Material Integration in Roller-Compacted Concrete Pavements: A Comprehensive Review of Mechanical Properties, Durability, and Environmental Benefits

Arya Nouri [1], Mohammadreza Khakbaz [2]*

[1] Ph.D. candidate, Transportation Engineering Group, Faculty of Civil Engineering, Iran University of Science and Technology, Tehran, Iran.

[2] Ph.D. Student, Department of Civil Engineering, Highway & Transportation Engineering, Iran University of Science and Technology, Tehran, Iran.

*Correspondence should be addressed to Mohammadreza Khakbaz, Department of Civil Engineering, Iran University of Science and Technology, Tehran, Iran. Email: mohammadreza_khakbaz@civileng.iust.ac.ir

ABSTRACT

The escalating global demand for sustainable infrastructure has established Roller-Compacted Concrete (RCC) as a premier alternative to conventional paving methods, offering a strategic balance between rapid construction, cost-efficiency, and high structural capacity. This study provides a comprehensive assessment of integrating alternative aggregates—specifically Recycled Concrete Aggregate (RCA), Reclaimed Asphalt Pavement (RAP), Electric Arc Furnace Steel Slag (EAFSS), and crumb rubber—in conjunction with supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag. The analysis reveals that while high-absorption materials like RCA and EAFSS elevate the optimum moisture content, hydrophobic components like RAP generally curtail water demand, facilitating easier densification. Mechanically, the inclusion of recycled materials typically induces a controlled reduction in compressive and flexural strengths; however, the judicious addition of silica fume or GGBFS can effectively counteract these deficits by refining the interfacial transition zone (ITZ) and densifying the internal pore structure. Ultimately, the findings demonstrate that replacing up to 50% of natural aggregates with recycled variants, when paired with optimized SCM dosages, yields a technically robust and environmentally responsible pavement solution. This research underscores the viability of these alternative materials as a pathway toward resource-efficient infrastructure, capable of meeting rigorous performance standards while substantially lowering the carbon footprint of modern pavement construction.

Keywords: Roller Compacted Concrete, Alternative materials, Recycled asphalt, Sustainable development, Environment modelling, smartphone sensor

Copyright © 2026, Mohammadreza Khakbaz. This is an open access paper distributed under the Creative Commons Attribution License. Journal of Civil Engineering and Materials Application is published by (ISNet); Journal p-ISSN 2676-332X; Journal e-ISSN 2588-2880.

1. INTRODUCTION

Distinguished by its zero-slump consistency, Roller-Compacted Concrete (RCC) is a dry mix formulated with a minimal water-to-cement ratio, continuous grading, and significant density to ensure high mechanical compaction potential. Distinct from conventional concrete, which necessitates internal vibration for consolidation, RCC is placed via standard asphalt

paving equipment and compacted using heavy vibratory rollers. This specific methodology has established RCC as a financially and operationally viable option for pavements and mass structures in recent decades, driven largely by accelerated project timelines, reduced expenditures, minimal formwork needs, and a decreased reliance on extensive reinforcement. Originally emerging in Canada during the 1970s for industrial yards and lumber storage depots, the technology was subsequently embraced across Europe and the United States. Facilitated by improvements in mixing technology, moisture control, and aggregate grading, the scope of its application has broadened to include heavy-traffic pavements, ports, container terminals, industrial facilities, heavy-duty parking areas, mining access roads, airport runways, and even specialized structures like gravity dams. A standard RCC mixture incorporates 75–85% aggregate with precisely controlled continuous grading, Portland cement (Type I or II), and supplementary cementitious materials like fly ash or slag to improve workability and mitigate hydration heat. The formulation maintains a very limited water content, and may utilize admixtures such as retarders or superplasticizers compatible with dry concrete. When compacted to equilibrium, this composition achieves compressive strengths ranging from 28–41 MPa, flexural strengths of 3.5–7 MPa, and a modulus of elasticity of 14–41 GPa. Furthermore, it exhibits low shrinkage, excellent fatigue resistance, impermeability, and robust durability against freeze–thaw cycles, abrasion from heavy traffic, and environmental stressors. The integrity of successful RCC placement is contingent upon rigorous mixture moisture control, precise aggregate grading, layer thickness, and compaction. The construction protocol mandates subgrade preparation to a minimum 95% Proctor density, spreading with graders or specialized finishers, and multi-pass compaction using vibratory and smooth steel rollers. Additionally, the formation of longitudinal and transverse joints is essential to mitigate cracking, alongside rapid surface curing using protective membranes or wet coverings. Implementing RCC for pavements offers substantial benefits over asphalt, including marked reductions in initial construction costs, minimal maintenance obligations, and superior resistance to rutting and abrasion. It also demonstrates favorable performance under heavy axle loads and an extended service life. In comparison to conventional jointed plain concrete pavements (JPCP), RCC presents a more sustainable solution by curtailing formwork, eliminating or minimizing reinforcement and dowels, reducing construction volumes, and simplifying large-scale execution. However, implementation is not without obstacles; issues such as high sensitivity to moisture control, potential segregation during transport, a comparatively coarser surface finish before final dressing, the need for specialized equipment, and the necessity for trial sections to calibrate optimal moisture content and compaction procedures must be carefully managed. Regulatory frameworks such as ASTM C1170 for flexural strength, ASTM C39 for compressive strength, ASTM C1602 for water quality, ACI 207.5R for mix design, and AASHTO guides establish the scientific and empirical basis for safe and functional RCC application. To conclude, RCC combines low construction cost, rapid execution, remarkable durability, high load-bearing capacity, and excellent abrasion and fatigue resistance. Its minimal maintenance requirements and reliable performance in harsh environments make it suitable for large-scale projects. These attributes have positioned RCC as one of the most efficient and sustainable options for heavy-duty pavements and infrastructure worldwide, prompting extensive research into mix design, mechanical behavior modeling, mechanistic–empirical design methods, and the evolution of RCC construction technology in recent years [1-6]. Economic analyses consistently demonstrate that Roller-Compacted Concrete Pavement (RCCP) is more cost-effective than both conventional Hot Mix Asphalt (HMA) and traditional cast-in-place concrete systems. Beyond its superior strength and durability, RCCP is particularly suitable for applications requiring high structural capacity, such as parking areas, port facilities, military zones, and roadway shoulders. Consequently, the use of Roller-Compacted Concrete Pavement can be justified as an efficient and economically viable solution, providing a competitive alternative to conventional asphalt and concrete paving methods [2, 7].

A prevalent methodology regarding the design of Roller-Compacted Concrete (RCC) mixtures is grounded in soil compaction principles [8]. Due to the distinct attributes inherent in RCC mixture design and construction, this pavement category represents a fiscally and ecologically viable alternative [2, 9]. While the fabrication of Roller-Compacted Concrete

Pavement (RCCP) parallels that of Jointed Plain Concrete Pavement (JPCP), it diverges principally where RCC employs a placement technique akin to soil compaction and integrates an elevated volume of fine aggregates. Additionally, the RCC mixture characteristically features reduced water and cement volumes relative to conventional JPCP, yet attains equivalent mechanical strength and performance metrics [2]. Conversely, in terms of material deposition, the construction methodology for Roller-Compacted Concrete Pavement (RCCP) mirrors that of asphalt pavements. Standard asphalt finishers are utilized to distribute the RCC mixture uniformly across the prepared subgrade. Subsequent to spreading, compaction is executed via standard vibratory or pneumatic-tire rollers, replicating the densification procedures used in asphalt construction [2, 5, 9-15].

Figure 1 depicts the standard machinery employed for the mixing, deposition, and densification of Roller-Compacted Concrete (RCC) materials. Typically, RCC pavements are composed of two functional strata: the base layer and the surface (wearing) course. In base layer applications, the cement content parallels that of low-cement, eco-efficient concrete or dry lean concrete mixtures. In contrast, surface layer implementation necessitates superior compressive strength—usually ranging from 28 to 41 MPa at 28 days under water-curing conditions—to ensure adequate structural integrity and surface durability [10, 16-19].

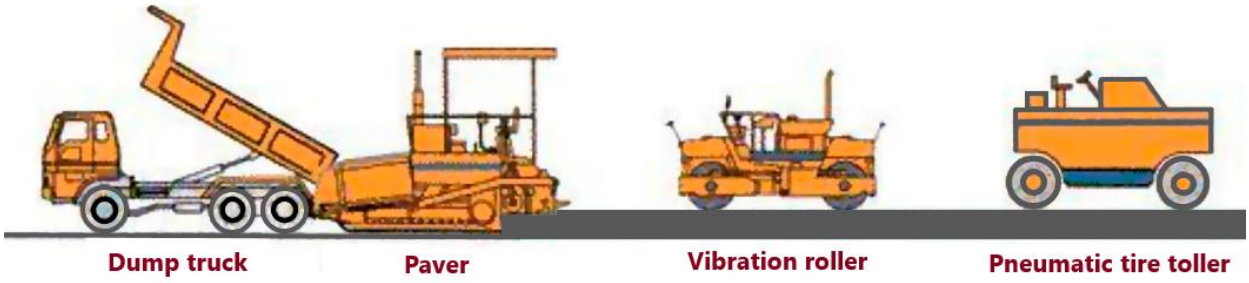

Figure 1. Machinery and equipment used for the construction of roller-compacted concrete pavement [6]

Recently, the pavement construction sector has placed a premium on environmental stewardship and sustainable development. Strategies such as mixture design optimization, novel execution methods, and a marked reduction in virgin material consumption are propelling the shift toward ecologically conscious infrastructure [20-26]. Minimizing the depletion of virgin aggregates while integrating alternative sources stands as the primary mechanism for achieving these sustainability goals. Successfully implemented alternative aggregates in Roller-Compacted Concrete Pavement (RCCP) include Recycled Concrete Aggregate (RCA), Mixed Recycled Concrete Aggregate (MRCA), Reclaimed Asphalt Pavement (RAP), Electric Arc Furnace Steel Slag (EAFSS), and crumb rubber. Deploying these materials enhances construction efficiency while substantially lowering project costs. The primary benefits include reduced procurement and logistics expenses, the mitigation of waste disposal issues, and a decrease in carbon emissions. Consequently, the integration of recycled aggregates is fundamental to the advancement of environmentally responsible infrastructure [27, 28].

Complementing the use of alternative aggregates, the substitution of ordinary Portland cement with pozzolanic materials represents a parallel strategy for sustainability. Historically, Portland cement served as the dominant binder in RCC pavements. However, the environmental footprint of cement manufacturing has prompted researchers to explore supplementary cementitious materials (SCMs) as partial or full replacements. This transition is largely a response to the energy-intensive nature of cement production, which is responsible for roughly 8% of global anthropogenic CO_2 emissions. This statistic underscores the urgency of adopting pozzolanic or alternative binders in concrete formulations [2].

However, deploying recycled materials in RCC is not devoid of challenges. For example, Recycled Concrete Aggregates (RCA) can precipitate a significant decline in concrete strength [29]. Likewise, the poor interfacial bonding between bitumen-coated Reclaimed Asphalt Pavement (RAP) and the cementitious matrix can result in considerable strength loss [30, 31]. Currently, while RAP reuse is standard practice, surplus volumes remain problematic; for instance, U.S. highway contractors generated an estimated 85 million tons of

excess RAP by 2015 [27]. Consequently, effective management and utilization strategies for these surpluses are heavily advocated by industry experts. Laboratory trials indicate that RAP can be effectively integrated into pavement systems, provided that optimal proportions are established via rigorous testing of fresh and hardened properties [32]. Despite minor compromises in compressive strength, RAP-enhanced concrete exhibits superior ductility, crack resistance, and load-bearing capacity relative to conventional virgin-aggregate concrete [27, 33]. Furthermore, fracture mechanics under varied loading modes remains a pivotal consideration. Research suggests that adding crumb rubber to RCC can boost fracture toughness, offsetting minor reductions in compressive strength [34-37]. Additionally, coarse Electric Arc Furnace Steel Slag (EAFSS) can variably impact strength depending on its surface texture and angularity. Ultimately, the mechanical behavior of RCC pavements across curing timelines is dictated by aggregate characteristics, gradation, water-to-cement ratio, and admixture usage [38, 39].

Integrating pozzolanic materials with recycled aggregates significantly bolsters both the compressive strength and durability of the cementitious matrix in Roller-Compacted Concrete (RCC), ultimately optimizing the overall performance of the pavement. These benefits stem from the pozzolanic reaction, where available silica and alumina interact with calcium hydroxide from cement hydration to generate supplementary calcium silicate hydrate (C–S–H) gel. This process densifies the concrete's microstructure, curtails porosity, and fortifies resistance against environmental stressors like carbonation and chloride penetration. Reactivity hinges largely on particle size, amorphous content, and chemical composition, with finer, more amorphous materials typically demonstrating superior performance. Environmentally, incorporating pozzolans offers distinct advantages: it lowers energy consumption and CO_2 emissions linked to cement production while repurposing industrial by-products. Pozzolans fall into two categories: natural and artificial. Natural variants like volcanic ash have historical precedence, whereas artificial types—such as silica fume, slag, and fly ash—dominate modern practice due to their consistency and higher reactivity. Crucially, pozzolans exhibit a slow hydration rate and low heat evolution, which helps prevent thermal cracking in mass concrete and thick RCC layers. Research confirms that artificial pozzolans significantly impact RCC properties, enhancing workability, limiting shrinkage, and boosting long-term durability. Consequently, pairing recycled aggregates with pozzolanic materials represents a viable strategy for creating economical, sustainable RCC pavements, consistent with global infrastructure trends [40-43].

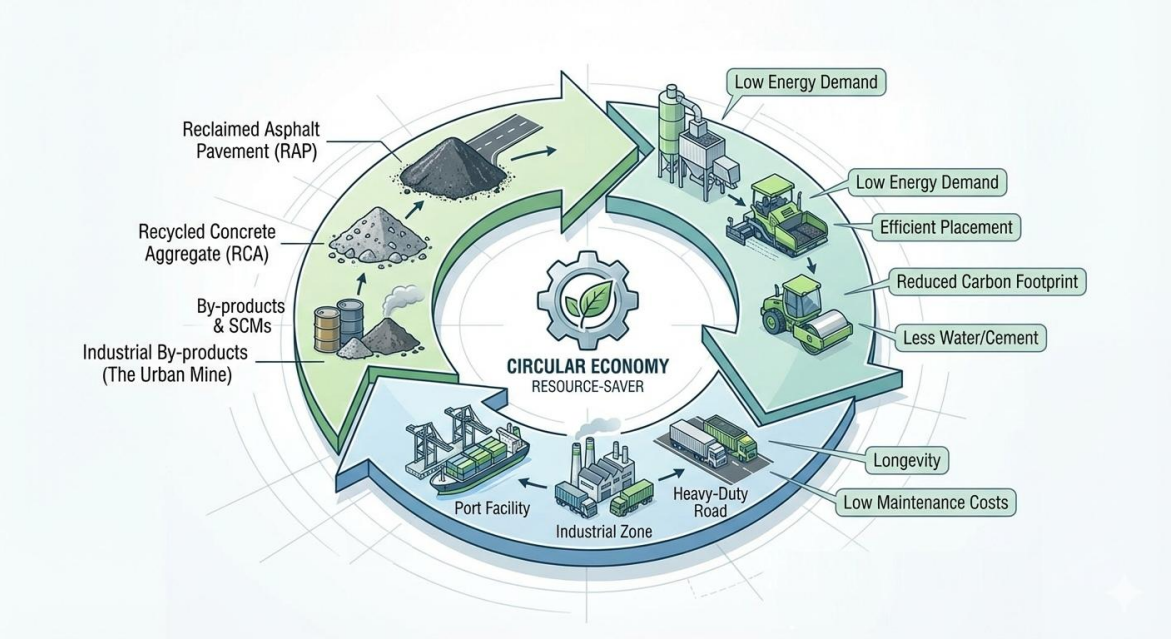

Figure 2. Circular-economy concept for RCCP using RAP, RCA, and SCMs, highlighting sustainability and performance benefits

The present study evaluates the utilization of alternative and recycled materials in Roller-Compacted Concrete (RCC) pavements. Since RCC typically contains an aggregate volume 10–15% higher than conventional concrete, incorporating alternative aggregates is a uniquely effective strategy. Adopting these materials yields substantial environmental benefits, namely reduced demand for natural aggregates, alleviation of waste disposal issues, and lower carbon emissions. However, apprehension regarding mechanical performance and technical viability persists. Therefore, this paper provides a comprehensive analysis of the advantages and limitations of recycled and alternative materials in RCC, emphasizing their implications for sustainable infrastructure.

2. PROPERTIES OF ALTERNATIVE MATERIALS IN ROLLER-COMPACTED CONCRETE PAVEMENTS (RCCP)

The selection of alternative aggregates for Roller-Compacted Concrete (RCC) demands a rigorous evaluation of structural and mechanical attributes to guarantee compliance with performance standards. Given that these materials display significant variability, critical assessment is mandatory. Specifically, the compatibility of alternative aggregates with the mixture's mechanical and durability prerequisites is paramount. For example, Recycled Concrete Aggregate (RCA) and Reclaimed Asphalt Pavement (RAP) present divergent physical traits: RCA is characteristically encased in residual mortar [44], whereas Mixed Recycled Concrete Aggregate (MRCA) incorporates porous adhered mortar and an elevated ceramic content, resulting in heightened water absorption [45]. Conversely, RAP is derived via the milling of deteriorated asphalt, yielding particles coated with a hydrophobic bituminous layer that inhibits moisture intake [27, 46]. Quantitatively, the residual mortar in RCA spans 30–60%, with a specific gravity hovering between 2.1–2.5 [29]. In the case of RAP, bitumen content fluctuates between 2–7.5%, while specific gravity ranges from 1.8 to 2.6. Consequently, the porous mortar in RCA drives higher water absorption, while RAP's hydrophobic coating acts as a barrier [47, 48]. Electric Arc Furnace Steel Slag (EAFSS), a byproduct of steel manufacturing, boasts exceptional mechanical properties. Distinguished by its black, stony appearance and rough texture, EAFSS possesses a substantial specific gravity (approximately 2.9–3.4), high resistance to abrasion, and superior crushing strength, rendering it ideal for RCC [38, 49]. Nevertheless, the potential for expansion and volumetric instability due to free lime and magnesium oxide requires mitigation via precise processing. Once treated, however, EAFSS emerges as a viable alternative aggregate [38]. Figure 3 delineates the alternative aggregates studied alongside their general properties [50, 51]. Additionally, Table 1 compiles pivotal research on the utilization of sustainable aggregates in RCC mixtures.

Figure 3. Specifications of the replacement aggregates used in roller-compacted concrete pavement [50, 51]

Considerable academic inquiry has focused on the variables governing the use of alternative aggregates. Pozzolanic materials, comprising fine particulates of silica and alumina, possess no intrinsic binding value yet exhibit reactivity in the presence of moisture and calcium hydroxide to form

cementitious compounds analogous to Portland cement. These chemical interactions refine the concrete microstructure and fortify the properties of the interfacial transition zone (ITZ). While pozzolans vary regarding origin, physical characteristics, and chemical composition, they consistently modify concrete properties through pozzolanic or hydraulic activity. The extent of their reactivity is contingent upon chemical composition, processing conditions, molecular structure, and particle size—all of which directly impact concrete quality and performance. Mastery of these factors empowers engineers to optimize mixture designs, thereby bolstering strength, durability, and workability while simultaneously curtailing costs [11, 51-53].

Table 1. Summary of Technical Literature on Sustainable Material Integration in RCCP

No.	Research Title	Key Findings	Ref
1	Performance evaluation of sustainable materials in roller compacted concrete pavements	Provides evidence-based insights on how sustainable materials affect RCC microstructure, strength, and durability	[54]
2	Experimental Investigation of Sustainable Roller-Compacted Concrete Pavement (RCCP) Reinforced with Natural Fibers	Natural fiber reinforcement in RCCP enhances mechanical properties, durability, and environmental performance, with coconut fiber showing the best balance of strength and sustainability	[55]
3	Material Selection and Mixture Proportioning Methods for Sustainable Roller-Compacted Concrete Pavements	Optimal sustainable materials and mix design are key to high-performance and durable RCCP	[42]
4	Life cycle assessment, mechanical properties, and durability of roller compacted concrete pavement containing recycled waste materials	Using ceramic waste aggregates and coal waste powder in RCCP improves mechanical properties, durability, and environmental performance, reducing greenhouse gas emissions and global warming potential.	[43]
5	Fabricating a Sustainable Roller Compacted Concrete Containing Recycled Waste Demolished Materials	The use of recycled concrete and asphalt pavement aggregates as alternative materials in RCCP has shown potential for improving sustainability, reducing lifecycle costs, and enhancing mechanical properties, with further research needed to optimize mix ratios and explore future applications.	[5]
6	Strength Evaluation of Roller-Compacted Concrete using Waste Clay-Brick as Aggregate	Incorporating waste clay-brick as partial aggregate and filler in RCC improves compressive, flexural, and tensile strength through internal curing, offering a sustainable approach for high-performance concrete.	[56]
7	Use of concrete road recycled aggregates for Roller Compacted Concrete	Using concrete road recycled aggregates in RCC provides similar compactness to natural aggregates, though compressive strength is slightly lower, demonstrating feasibility for sustainable pavement and sub-base applications	[51]
8	Roller compacted concrete with contaminated recycled aggregates	Using contaminated recycled aggregates in RCC affects mechanical properties and durability, highlighting the need to account for contaminants like chlorides and sulfates for safe and sustainable applications.	[57]
9	Mechanical performance of roller compacted concrete with recycled concrete aggregates	Using coarse recycled concrete aggregates (RCA) in RCC is feasible up to 100% replacement, providing sustainable and effective solutions for road pavement bases without compromising mechanical performance.	[58]
10	Roller Compacted Concrete with Recycled Concrete Aggregate for Paving Bases	RCC with recycled concrete aggregate (RCA) maintains adequate mechanical and physical properties for paving bases, even at 30% RCA replacement, meeting Brazilian standards for base layer applications.	[59]
11	Utilization of alternative aggregates for roller compacted concrete pavements	This article investigates the use of alternative aggregates (RCA, RAP, EAF slag, and rubber tire) in roller-compacted concrete pavement (RCCP), demonstrating that they can be effectively used at specific replacement levels, with techniques for improving performance, and highlights the need for further research on optimal mix ratios.	[39]
12	Experimental investigation of using cross-linked polyethylene waste as aggregate in roller compacted concrete pavement	This study investigated using cross-linked polyethylene (XLPE) waste as coarse aggregate in roller-compacted concrete pavement (RCCP). Replacing 5% of natural coarse aggregate with XLPE improved 28-day tensile, compressive, and flexural strength, increased ductility and cracking resistance, and reduced density and compaction time.	[60]

13	Experimental testing and modelling of roller compacted concrete incorporating RAP waste as aggregates	This study evaluated using reclaimed asphalt pavement (RAP) as aggregate in roller-compacted concrete (RCC). Increasing RAP content reduced compressive, tensile, and elastic modulus properties. Compressive strength models (Bolomey, Tango, de Larrard) were tested, showing de Larrard best explains strength reduction due to weaker aggregate-cement adhesion.	[61]

3. Effect of Alternative Materials on the Properties of Roller-Compacted Concrete Pavement

The integration of alternative materials into roller-compacted concrete (RCC) has garnered heightened interest, driven by a convergence of environmental, economic, and performance incentives. The incorporation of recycled substances or industrial by-products—notably recycled concrete aggregates (RCA), fly ash, silica fume, steel slag, and reclaimed asphalt pavement (RAP)—exerts a profound influence on both the fresh and hardened states of RCC. Specifically, these constituents alter critical parameters ranging from moisture content, workability, and compact ability to density and overall mechanical performance. This includes impacts on compressive, flexural, and tensile strengths, alongside abrasion resistance. Consequently, a granular understanding of how these alternative materials behave is essential for optimizing mix design and ensuring durability. Moreover, this knowledge is pivotal for advancing sustainable pavement solutions that reduce dependence on natural resources. This section examines the specific influence of alternative materials on roller-compacted concrete (RCC), focusing distinctly on fresh and mechanical properties. Key metrics analyzed include optimum moisture content, workability, maximum dry density, compressive strength, flexural strength, indirect tensile strength, and abrasion resistance.

with data in Table 3, which lists axial forces at the CG-RB connection.

3.1. Fresh Properties of Concrete Incorporating Alternative Materials

This section investigates the fresh properties of roller-compacted concrete (RCC) formulations incorporating alternative materials. Paramount among these characteristics is optimum moisture content, a critical determinant of performance and workability. Additionally, the study examines maximum dry density, given its direct impact on compactability and the structural integrity of the mixture. Together, these parameters highlight the critical need for rigorously evaluating fresh properties to facilitate precise optimization of the mix design and production protocols.

3.1.1. Optimum Moisture Content

Given that roller-compacted concrete (RCC) relies on static or vibratory rollers for consolidation, its mix design frequently mirrors procedures established for soil compaction. In this context, attaining sufficient moisture content is critical to achieving maximum density. The Modified Proctor test (ASTM D1557) remains the standard and widely accepted protocol for determining the optimum moisture content (OMC) of RCC mixtures. However, when friable aggregates are utilized, the Standard Proctor test (ASTM D698) serves as a viable alternative. Additionally, the Superpave Gyratory Compactor (SGC) has gained traction among researchers due to its ability to accurately simulate field compaction conditions during both OMC determination and specimen preparation [62-65].

Conventionally, the optimum moisture content of RCC mixtures formulated with natural aggregates falls between 5% and 8% of the total dry mass. In contrast, mixtures incorporating recycled concrete aggregates (RCA) demonstrate a marked increase in water demand; moderate replacement levels (5–30%) raise the OMC by approximately 1.5–1.6% [59]. At higher replacement ratios (50–100%), this surge is even more pronounced, with OMC values exceeding conventional mixes by 25–35% [58]. This phenomenon is largely driven by the residual mortar adhered to the recycled aggregate surfaces, which significantly amplifies water absorption. Moreover, the provenance of the recycled aggregates matters. For instance, aggregates derived from mixed construction and demolition waste have been shown to elevate OMC by 35–53%, a spike attributed to the significant proportion of ceramic waste particles

(11.4–23.4%) that necessitate additional water for maximum compaction [2, 45, 66].

Paralleling the behavior of recycled concrete aggregates, the inclusion of electric arc furnace steel slag (EAFS) at 50–100% replacement levels can drive the optimum moisture content up by 15–21%. This confirms that EAFS aggregates require higher water volumes to achieve maximum compaction. However, introducing fly ash can counterbalance this demand, leveraging the ball-bearing effect of its spherical particles to enhance workability [67]. Conversely, the use of reclaimed asphalt pavement (RAP) generally induces the opposite effect, reducing OMC by approximately 8–12% due to the hydrophobic asphalt coating. Exceptions exist, however; some studies report OMC increases of up to 12% with RAP, likely stemming from particle agglomeration trapping water within internal voids [61, 68-71]. Similarly, research on crumb rubber indicates a reduction in OMC [34]. The low absorption capacity of rubber leaves more free mortar available, thereby improving lubrication, compaction efficiency, and consistency. Broadly speaking, materials with high water absorption capacity, like RCA and steel slag, elevate OMC, whereas hydrophobic or low-absorption materials, such as RAP and crumb rubber, tend to lower it. Nevertheless, anomalies occur, such as when RAP agglomerations or fine dust alter the internal moisture distribution [2, 39].

Sustaining precise moisture levels in concrete mixtures—especially those involving supplementary cementitious materials (SCMs)—boosts particle mobility and ensures voids between aggregates are filled more effectively. Particle surface morphology significantly dictates the water and cement volumes necessary to fine-tune mortar workability. SCMs generally feature a broader specific surface area compared to ordinary Portland cement; their finer granularity fosters intensified interaction within the surrounding matrix. As a result, replacing cement with these additives typically escalates water demand in roller-compacted concrete (RCC) mixtures. The scale of this rise in optimum moisture content (OMC) hinges on the specific type and dosage of the SCM utilized. Among evaluated materials, silica fume precipitates the steepest climb in optimum moisture content (OMC). This acute spike in moisture requirement stems primarily from the exceptionally vast surface area of silica fume particles. Consequently, silica fume integration necessitates a high-range water reducer, substantially inflating the mixture's overall cost. However, experimental data suggests this hurdle can be mitigated by introducing reclaimed asphalt pavement (RAP) and crumb rubber. The weathered bitumen coating on RAP particles lowers porosity and water absorption relative to fresh aggregates, effectively boosting the available free water within the RCC mix. Conversely, fly ash—characterized by smooth, spherical particles—possesses a reduced surface area and thus demands less moisture than silica fume. Furthermore, when RCC mixtures incorporate 20–60% ground granulated blast furnace slag (GGBFS), OMC rises by approximately 1–11%. This distinct elevation in optimum moisture is attributable to the expanded surface area of slag particles and their constrained early-stage reactivity relative to Portland cement [54, 72, 73].

In an experimental effort to propel sustainable methodologies in roller-compacted concrete pavement (RCCP) production, researchers probed the impact of waste rubber as an alternative aggregate on the mechanical and physical integrity of RCC mixtures. Three distinct forms of waste rubber—powder, crumb, and shredded—were integrated at seven volumetric replacement tiers (0%, 2.5%, 5%, 7.5%, 10%, 20%, and 30%) to assess their viability as partial or total substitutes for natural aggregates. The investigation systematically gauged fluctuations in unit weight, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and ultrasonic pulse velocity (UPV) across the spectrum of rubberized mixtures. Additionally, microstructural analysis via scanning electron microscopy (SEM) was performed to elucidate the interfacial bonding and internal pore architecture resulting from rubber inclusion. Results revealed a distinct degradation in compressive, flexural, and splitting tensile strengths, alongside a dip in the elastic modulus, as waste-rubber content increased. Notwithstanding this drop in strength metrics, rubberized RCC mixtures demonstrated improved ductility and a marked decrease in density, facilitating the production of lightweight concrete. Crucially, the results showed that RCC containing 10% waste rubber could still attain a compressive strength of roughly 30 MPa, validating its aptitude for pavement applications. Moreover, mixtures with up to 30% rubber content yielded RCC that was up to 15% lighter, underscoring potential advantages

for engineering scenarios requiring reduced dead load. Ultimately, this research highlights the potential of substituting natural aggregates with waste rubber to fabricate greener RCC pavements, simultaneously tackling the environmental and economic hurdles linked to disposing of end-of-life rubber materials [74].

3.1.2. Maximum Dry Density

Integrating recycled concrete aggregate (RCA) into roller-compacted concrete (RCC) mixtures tends to lower the maximum dry density, principally because of the aggregate's reduced specific gravity [59]. Interestingly, the gradient of the optimum moisture content–maximum dry density curve often flattens compared to that of control RCC mixtures. This suggests that RCC mixtures incorporating RCA can accommodate equivalent or even broader variations in moisture content without compromising dry density during compaction [58]. Paralleling this, the addition of low-density reclaimed asphalt pavement (RAP) and crumb rubber can reduce MDD by roughly 5% and 7%, respectively [75, 76]. However, RAP offers a distinct benefit: the cohesive binder film and smoother particle geometry enhance workability and compatibility [77].

In contrast, incorporating electric arc furnace steel slag—owing to its higher specific gravity—boosts the maximum dry density of RCC mixtures by about 0.7% to 3.9%. Ultimately, regardless of the alternative aggregate selected, variations in maximum dry density remain marginal. This underscores the viability of alternative aggregates, as the hardened strength of RCC is inextricably tied to the maximum compaction achieved in the fresh state [39, 42].

Partially substituting cement with supplementary materials typically lowers the maximum dry density (MDD) of RCC mixtures. This occurs because these additives are often physically lighter and possess a lower specific gravity than the cement they replace. Consequently, the overall mixture mass drops. For instance, replacing cement with fly ash at levels of 20%, 40%, and 60% causes density decreases of approximately 1.2%, 4.6%, and 6.8%, respectively. Such reductions can ripple through to workability, strength, and overall performance [78]. Likewise, combining 15–30% fly ash with 50% RAP resulted in a 4.2% to 4.9% density drop compared to controls [69]. This decline is primarily driven by the lower specific gravity of fly ash relative to Portland cement [76].

Moreover, data indicates that adding 5% and 10% silica fume to RAP-based RCC mixtures lowered maximum dry density by about 2.8% and 5.2%, respectively [69]. Previous research highlights a diminishing return: as silica fume replacement increases, the rate of density loss slows. This happens because the ultra-fine particle size and high pozzolanic reactivity of silica fume allow it to fill micro-voids in the cement matrix more effectively than other supplements. So, while silica fume initially lowers density due to its light weight, higher dosages counteract this by densifying the microstructure. Ultrasonic pulse velocity (UPV) measurements back this up. Higher silica fume content consistently boosts UPV values, signaling a denser cement paste and a better interfacial transition zone (ITZ). These improvements cut down internal defects, enhancing matrix continuity and stiffness, which speeds up pulse transmission [76, 79].

Among alternative binders, ground granulated blast furnace slag (GGBFS) holds a distinct advantage: its specific gravity closely matches that of ordinary cement. This attribute allows GGBFS to minimize density loss (approximately 1%) compared to silica fume or fly ash. Consequently, GGBFS helps maintain the structural compactness essential for long-term mechanical performance and durability [80]. Overall, regardless of the material or dosage, density reductions generally stay below 10%. Therefore, replacing cement with these supplements is unlikely to drastically alter the fresh properties of RCC mixtures.

3.2. Mechanical Properties of Roller-Compacted Concrete Containing Alternative Aggregates

The following section evaluates the impact of alternative aggregates on critical mechanical properties of roller-compacted concrete (RCC), specifically encompassing compressive strength, flexural strength, indirect tensile strength, and abrasion resistance. Compressive and flexural strengths stand as fundamental parameters that dictate RCC pavement thickness design [39, 42, 81].

3.2.1. Compressive Strength

Compressive strength stands as a paramount metric for concrete quality control, necessitating precise selection of constituent materials. The inclusion of alternative aggregates can profoundly influence the compressive strength of RCC mixtures. For instance, the utilization of recycled concrete aggregate (RCA) can diminish the compressive strength of RCC mixtures by as much as 35%. Research indicates that compressive strength hinges on the RCA replacement level; a 30% RCA content may induce a 29% reduction [59], while total replacement may precipitate a drop of roughly 35% [58]. This decline stems from the presence of adhered old mortar on the RCA

surface, which typically compromises the interfacial transition zone (ITZ) between the aggregate and the nascent cement paste.

When RCA derives from heterogeneous parent materials, a more pronounced reduction in compressive strength (24–31%) has been reported compared to cases where RCA originates from a single non-blended source (12–18% reduction) [79, 82]. Analogous to RCA, the integration of crumb rubber and reclaimed asphalt pavement (RAP) also impairs compressive strength. Specifically, using crumb rubber at 5–30% replacement results in a 10–32% reduction [83]. The strength deficit is largely ascribed to the inferior bonding between cement paste and rubber particles. However, the addition of 5% crumb rubber may yield a beneficial effect due to enhanced particle interlocking and sufficient friction between rubber particles within the mixture [34].

Empirical data suggests that integrating RAP into RCC mixtures decreases compressive strength within the range of 9–67% [34, 75]. This drop is traced back to the bitumen coating surrounding RAP particles, which impedes robust bonding between the cement paste and RAP aggregates. The utilization of coarser RAP particles results in a milder reduction (about 25%), whereas finer RAP particles or blends induce more severe losses (40–60%) [75].

Literature reports divergent behaviors in RCC mixtures incorporating electric arc furnace steel slag (EAFSS), driven primarily by its porosity, structural morphology, water absorption, and interfacial transition characteristics [38, 67, 84, 85]. While some studies report declines in compressive strength, others observe improvements. For instance, one study noted that regardless of replacement level or particle size, the use of EAFSS resulted in compressive strength reductions of 5–39%. The existence of free lime and periclase (MgO) in EAFSS induces expansion, which in moist environments may cause volume increases of up to 10%. This instability renders unprocessed EAFSS unsuitable for Portland cement applications unless the material undergoes weathering for 3–12 months under moist outdoor conditions [67, 86]. Even with pre-treatment, reductions in strength are likely related to angularity and surface morphology, which impair bonding with the cement paste. In contrast, deploying coarse EAFSS aggregates at 50% and 100% replacement levels has been shown to enhance compressive strength by 6% and 14%, respectively—primarily due to their rough, angular texture that improves ITZ performance and boosts the load-bearing capacity. Consequently, while RCA and RAP tend to reduce compressive strength, EAFSS and crumb rubber demonstrate more complex behavior. Therefore, microstructural analyses are essential for elucidating the influence of these aggregates on RCC performance [38].

A survey of existing literature on supplementary cementitious materials (SCMs) underscores the generally beneficial effects on compressive strength. Two studies show that replacing cement with up to 40% ground granulated blast furnace slag (GGBFS) increased 28-day compressive strength by 2.67–4.5% [80, 87]. This enhancement is credited to cement hydration, pozzolanic reactions, and the latent hydraulic activity of slag. Curing duration and the concentration of calcium hydroxide (CH) generated during hydration are critical, as the CH concentration increases after 90 days, sustaining pozzolanic activity and generating additional C–S–H gel, thus bolstering strength.

Likewise, fly ash makes a positive contribution up to an optimal replacement level, while higher levels reduce strength. Studies show that at a 15% fly ash substitution rate, 28-day strength increases from 22.57 MPa to 25.89 MPa, whereas at 30% and 45% replacement, strength decreases by 19–47% [88]. This decline is linked to an elevated water–cement ratio and greater particle spacing, which delay the formation of a dense crystalline network [89]. Nevertheless, over extended periods, due to its slow reactivity, fly ash may produce strength comparable to or even exceeding that of the control mixture [78, 88].

Regarding silica fume, its elevated reactivity enhances compressive strength, particularly within the first 28 days [76, 79, 90]. The highest increase typically occurs from 7 to 28 days. However, when the replacement level rises from 10% to 15%, the rate of improvement plateaus, likely due to a scarcity of CH or available water to sustain pozzolanic reactions. Excess silica fume then acts as an inert filler and may agglomerate within the mixture [76, 79]. Studies also show that coupling silica fume with recycled aggregates, such as crumb rubber and RAP, can effectively compensate for strength losses by improving ITZ quality [69, 79, 91].

3.2.2. Flexural Strength

Flexural strength serves as a pivotal metric in RCC mix design and pavement structural analysis. It is dictated largely by the water–cement ratio and aggregate gradation. Consistent with compressive strength trends, the inclusion of RCA—regardless of particle size or replacement level—diminishes flexural strength by approximately 12–27% [58, 59]. As previously noted, the porous ITZ associated with RCA induces higher porosity and, consequently, compromised flexural performance.

Employing coarse crumb rubber at 5–30% replacement precipitates a drop in flexural strength of 24–31% [83]. However, some researchers report that a 5% addition can boost flexural strength by 3–4%, a phenomenon linked to reduced cement content (owing to the lower absorption of rubber) and superior particle interlock between rubber and aggregates [34].

Likewise, integrating RAP—regardless of particle size—incurs a 5–31% loss in flexural strength [34, 75]. While

the bitumen film compromises bonding with the cement paste, its viscoelastic properties augment mixture toughness [34]. Consequently, if the deficit in flexural strength is offset by structural design adjustments (e.g., thicker RCC slabs), the utilization of RAP can actually elevate the load-bearing capacity of RCC pavements [10].

Regarding RCC mixtures with EAFSS, finer slag particles can impair flexural strength by up to 27% due to suboptimal bonding with the cement paste. In contrast, full replacement with coarse slag aggregates can elevate flexural strength by up to 9% [38]. The rugose and angular texture of coarse EAFSS fortifies the ITZ and bolsters pavement structural capacity. Broadly speaking, RCC mixtures containing alternative aggregates—with the exception of coarse EAFSS—tend to display reduced flexural strength. Thus, further inquiry into the structural characteristics of EAFSS is requisite for a comprehensive evaluation [39, 42].

The addition of 1% nanosilica boosts flexural strength by approximately 20% and 60%, respectively. However, exceeding this threshold may stifle the rate of improvement. This plateau is ascribed to the high specific surface area of silica fume and the inherently low water content of roller-compacted concrete mixtures [76, 91]. Furthermore, a marginal uptick in flexural strength has been observed in RCC mixtures containing reclaimed asphalt pavement (RAP) when silica fume is introduced. Specifically, incorporating 5–10% silica fume resulted in a 1–5% increase in flexural strength. This improvement is driven mainly by the surplus of amorphous silica at higher replacement levels, which optimizes flexural performance.

Conversely, the pozzolanic activity of fly ash is not as pronounced as that of silica fume; consequently, at early ages, RCC mixtures containing 20–60% fly ash exhibit significantly lower flexural strength than control mixtures. Yet, at later ages, the maturation of pozzolanic reactions yields flexural strength values comparable to the control mix at replacement levels below 20% [78, 88]. Additionally, substituting cement with ground-granulated blast furnace slag (GGBFS) can offset the deficiency of calcium oxide (CaO) through the presence of magnesium oxide (MgO). When MgO content reaches approximately 8–10%, a slight strength gain is realizable. While increasing CaO, Al_2O_3, and MgO levels enhances hydraulic activity, higher SiO_2 contents tend to inhibit it [92].

Of the various mixtures analyzed, only those utilizing 40% ground granulated blast furnace slag (GGBFS) demonstrate flexural strength that is comparable to, or even superior to, that of the standard control mixture. In comparison, mixtures containing a higher proportion of slag, such as 60% GGBFS, exhibit a noticeable deterioration in flexural performance. This reduction is primarily attributed to the diminished alkalinity and the elevated water-to-cement ratio in these higher-slag mixtures. These factors impede the hydration process and microstructural development of the cementitious matrix, resulting in compromised bending resistance [80, 87].

3.2.3. Indirect Tensile Strength

Empirical evidence suggests that the indirect tensile strength (ITS) of RCC pavements diminishes by approximately 18% when fully substituted with coarse recycled concrete aggregate (RCA). This decline stems largely from the weaker interfacial bonding between the cement matrix and RCA particles, which possess reduced resistance to deformation before tensile failure. Moreover, the inclusion of ceramic waste within RCA-infused mixtures may erode ITS by up to 23% [58]. Parallel findings indicate that incorporating 30% crumb rubber can depress the ITS of RCC mixtures by roughly 23% [83].

Similarly, the integration of reclaimed asphalt pavement precipitates a reduction in ITS regardless of curing age [75]. For example, researchers observed that incorporating 16% coarse RAP can lower ITS by approximately 16%. In another instance, employing 100% coarse RAP resulted in a 26% decrease, a phenomenon driven mainly by the asphalt coating surrounding RAP aggregates. This coating impedes proper interfacial bonding between the cement paste and RAP particles, thereby compromising the mixture's integrity.

Additionally, incorporating coarse electric arc furnace steel slag (EAFSS) yields mixed results, with reported reductions ranging from 13% to 32% depending on the replacement level (30–100%) [86]. Conversely, other investigations noted an ITS increase of 25% and 32% when coarse EAFSS was deployed at replacement levels of 50% and 100%, respectively. Furthermore, the utilization of 50% fine EAFSS boosted ITS by approximately 25% [38]. Where reductions occur, they are typically ascribed to the higher surface area of fine EAFSS, which diminishes cohesiveness.

Synthesizing prior research, it is evident that the concurrent use of Recycled Concrete Aggregate (RCA) and Reclaimed Asphalt Pavement (RAP) in roller-compacted concrete (RCC) can induce a marked reduction in indirect tensile strength (ITS). This deficit poses potential risks to the structural performance and durability of RCC pavements. Consequently, rigorous laboratory investigations are required to comprehensively evaluate how various combinations of recycled materials influence indirect tensile behavior. Such data is vital for optimizing mix designs and ensuring the long-term

viability of pavements utilizing recycled components [39, 42].

Regarding pozzolanic materials, results mirror the trends observed in compressive strength. Replacing cement with 20% and 40% GGBFS increased 90-day ITS by 8.75% and 15.82%, respectively, whereas gains at a 60% replacement level were capped at 1.68% [80]. Curing time is pivotal in slag-containing mixtures: at early ages (3–7 days), ITS falters due to the slow reactivity of slag particles; however, for mixtures containing 50% slag and cured beyond 28 days, ITS surged by approximately 50% [87].

Investigations into fly-ash-modified RCC mixtures reveal that at a 15% replacement level, the ITS of 28- and 90-day specimens rises by about 22% and 12%, respectively, relative to the control. Nevertheless, escalating the replacement level triggers a considerable reduction in ITS [78, 88]. Over time, ongoing pozzolanic activity narrows the strength gap between fly-ash mixtures and the control [78]. The subdued reactivity of fly ash is principally linked to its larger particle size and lower silica content [93].

Silica fume, distinguished by its vast specific surface area and rich amorphous silica content, plays a far more dynamic role in microstructural enhancement than fly ash. Its ultrafine particles effectively fill micro voids and react rapidly with calcium hydroxide to generate supplementary C–S–H gel, the primary driver of strength development. Consequently, mixtures containing silica fume exhibit a significantly denser cement paste and a more refined interfacial transition zone (ITZ) compared to those with fly ash. Scanning electron microscopy (SEM) validates this: In RCC mixtures where 50% of aggregates are replaced with reclaimed asphalt pavement (RAP), the ITZ in silica-fume-modified mixtures appears distinctly denser, more uniform, and less porous than both the control and fly-ash variants. This microstructural refinement translates directly into mechanical gains. Specifically, adding just 5–10% silica fume results in a substantial ITS increase, ranging from 6.7% to 13.3%. These figures are notably higher than what is achievable using comparable quantities of fly ash, highlighting the superior densification and strengthening effects of silica fume in RCC containing RAP [72].

Coupling construction and demolition waste (CDW) with silica fume has proven to be an effective remediation strategy for addressing the mechanical limitations of recycled aggregates. Recycled particles typically possess higher porosity, weaker bonding surfaces, and residual microcracks, all of which compromise strength and durability. Silica fume, via its ultrafine particle size and high pozzolanic activity, significantly bolsters matrix density and bond strength within the interfacial transition zone (ITZ). Data indicates that incorporating 5–10% silica fume into RCC mixtures containing large proportions of CDW—specifically where 50% and 75% of natural aggregates were replaced—resulted in notable ITS improvements. The ITS increased by 2.9% in the 50% replacement mixture and by 10.8% in the 75% mixture. These gains are particularly significant as they effectively offset the substantial initial strength reductions of 10.5% and 17.2% observed when CDW aggregates were used without silica fume. Thus, silica fume not only mitigates the detriments of recycled aggregates but can also partially restore and enhance the mechanical performance of the final RCC mixtures [79].

3.2.4. Abrasion Resistance

Assessing the abrasion resistance of roller-compacted concrete (RCC) pavements is vital to guarantee superior riding quality. This resistance is contingent upon aggregate quality and the mixture's compressive strength. Introducing alternative aggregates with diverse characteristics—ranging from compatibility and water absorption to surface texture—can profoundly impact abrasion performance. Multiple studies indicate that incorporating reclaimed asphalt pavement (RAP) may escalate mass loss during testing; however, the specific surface texture of the RAP is a determinant factor [75]. For instance, RAP aggregates with a rougher texture and lower asphalt content may resist degradation more effectively, whereas smoother particles with higher asphalt content tend to suffer substantial surface wear.

Recycled aggregates like RAP and construction and demolition waste (CDW), due to their inferior physical and mechanical properties relative to natural aggregates, generally compromise the abrasion resistance of concrete. These materials may also detrimentally affect the interfacial transition zone (ITZ) between the cement paste and the aggregates. Data suggests that in mixtures fully replaced with CDW, abrasion resistance drops by approximately 20%. Conversely, the addition of silica fume bolsters resistance by refining cement paste quality and densifying the overall matrix. Specifically, replacing 10% of the cementitious material with silica fume yields a 43.33% improvement. In mixtures where 75% of aggregates are replaced by CDW, employing 10% silica fume slashes groove depth from 13.85 mm to 7.26 mm. Other studies demonstrate that pairing silica fume with RAP reduces mass loss; for example, in mixtures containing 5% and 10% silica fume alongside 50% RAP, mass loss improved by 15% and 18%, respectively. Unlike silica fume, replacing Portland cement with 15% and 30% fly ash exacerbates abrasion wear by approximately 14% and 22% compared to mixtures containing 50% RAP. In RCC mixtures, elevating the replacement level of ground-granulated blast furnace slag (GGBFS) initially triggers higher mass loss at early ages

(3–7 days); however, at 28 days, mass loss diminishes when the replacement level reaches 50% [72, 87, 94].

4. CONCLUSION

Employing alternative aggregates in roller-compacted concrete (RCC) pavements offers distinct economic and environmental benefits, specifically regarding the conservation of natural resources and the reduction of material-related construction costs. The results of this investigation demonstrate that recycled aggregates, when integrated with precision, can boost workability and facilitate the creation of sustainable pavement materials without sacrificing critical engineering performance. While the asphalt coating on Reclaimed Asphalt Pavement (RAP) impedes interfacial bonding between the cement matrix and aggregate particles, it does not drastically compromise strength or porosity at replacement levels up to 50%, suggesting that moderate RAP usage remains structurally viable.

Evidence suggests that the efficacy of Recycled Concrete Aggregate (RCA) hinges largely on the quality of the parent material; nonetheless, substituting up to half of the natural aggregates with RCA can still yield RCC mixtures with sufficient mechanical resistance. Likewise, the inclusion of Electric Arc Furnace Steel Slag (EAFSS) boosts maximum dry density due to its high specific gravity, though its implementation necessitates increased mixing water and rigorous management of free CaO content to avert volumetric instability. Crumb rubber, characterized by its low specific gravity, may impair compact ability, yet at low replacement levels—typically up to 5%—it can enhance mixture workability and provide advantageous deformability characteristics.

Concurrently, integrating Supplementary Cementitious Materials (SCMs) is a proven strategy for bolstering the chemical reactivity and physical integrity of the RCC matrix. When dosed optimally, SCMs can significantly elevate both strength and long-term durability by densifying the pore network, strengthening the Interfacial Transition Zone (ITZ), and stimulating secondary hydration reactions.

Taken together, these findings demonstrate that the judicious application of recycled aggregates and SCMs can enable the production of roller-compacted concrete pavements with acceptable—and often superior—mechanical properties. Ultimately, alternative materials, when utilized in calibrated proportions, offer a viable pathway toward more sustainable, resource-efficient, and technically robust RCC pavement systems.

FUNDING/SUPPORT

Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT

Not mentioned any by authors.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFERENCES

[1] Aghaeipour, A. and M. Madhkhan, Mechanical properties and durability of roller compacted concrete pavement (RCCP)–a review. Road Materials and Pavement Design, 2020. 21(7): p. 1775–1798. [View at Google Scholar]

[2] Harrington, D., et al., Guide for roller-compacted concrete pavements. 2010. [View at Google Scholar]

[3] Salimi, A., N. Kamboozia, and M.R.M. Aliha, Experimental Investigation of the self-healing capability of Roller-Compacted Concrete (RCC) containing epoxy-filled glass tubes through fracture properties. Case Studies in Construction Materials, 2024. 21: p. e03369. [View at Google Scholar]

[4] Khayat, K.H. and N.A. Libre, Roller compacted concrete: field evaluation and mixture optimization. 2014. [View at Google Scholar]

[5] Shamran, A.S. and Z.K. Abbas, fabricating a sustainable roller compacted concrete containing recycled waste demolished materials: a literature review. Journal of Engineering, 2024. 30(03): p. 15–29. [View at Google Scholar]

[6] Ameri, M., N. Kamboozia, and M. Khakbaz, A review of Mechanical properties and durability of roller compacted concrete pavement (RCCP). Road, 2023. 32(119): p. 169–169. [View at Google Scholar]

[7] Hesami, S., et al., Mechanical properties of roller compacted concrete pavement containing coal waste and limestone powder as partial replacements of cement. Construction and building materials, 2016. 111: p. 625–636. [View at Google Scholar]

[8] 327, A.C. Guide to Roller-compacted Concrete Pavements. 2015. American Concrete Institute.

[9] Lee, S.W., Y.-H. Cho, and C. Park, Mechanical performance and field application of low cement based concrete under compaction energy. KSCE Journal of Civil Engineering, 2014. 18(4): p. 1053–1062. [View at Google Scholar]

[10] Chhabra, R.S., G.D. Ransinchung, and S.S. Islam, Performance analysis of cement treated base layer by incorporating reclaimed asphalt pavement material and chemical stabilizer. Construction and Building Materials, 2021. 298: p. 123866. [View at Google Scholar]

[11] Khakbaz, M., et al., Comprehensive review of the application of alternative materials in Roller Compacted Concrete Pavements (RCCP) with a sustainable development approach. Road, 2025. 33(123): p. 113–136. [View at Google Scholar]

[12] Algin, Z., A. Çiçekli, and S. Gerginci, Pareto-efficient utilisation boundaries of recycled asphalt pavement aggregates in roller-compacted concrete with Mohr-Coulomb parameter analysis. Road Materials and Pavement Design, 2025: p. 1–34. [View at Google Scholar]

[13] Kumar, B.R., et al., Sustainable roller compacted concrete: integrating ferrochrome slag and reclaimed asphalt pavement with cost and life cycle analysis. Innovative Infrastructure Solutions, 2025. 10(7): p. 298. [View at Google Scholar]

[14] Abd Almajeed, S.Q. and Z.K. Abbas, Eco-Friendly Roller Compacted Concrete: A Review. Journal of Engineering, 2024. 30(07): p. 144–165. [View at Google Scholar]

[15] Mostofinejad, D., et al., Advancing sustainable roller-compacted concrete using innovative pre-treatments: Enhancing aggregate-matrix bonding and mechanical performance. Case Studies in Construction Materials, 2025: p. e05551. [View at Google Scholar]

[16] Greene, J., A. Nazef, and B. Choubane, Thirty-year performance evaluation of two-layer concrete pavement system. Transportation research record, 2011. 2226(1): p. 21–29. [View at Google Scholar]

[17] Kasu, S.R., K. Manupati, and A.R. Muppireddy, Investigations on design and durability characteristics of cement treated reclaimed asphalt for base and subbase layers. Construction and building materials, 2020. 252: p. 119102. [View at Google Scholar]

[18] Singh, S., et al., Laboratory investigation of RAP aggregates for dry lean concrete mixes. Construction and Building Materials, 2018. 166: p. 808–816. [View at Google Scholar]

[19] Singh, S., G. Ransinchung, and K. Monu, Sustainable lean concrete mixes containing wastes originating from roads and industries. Construction and Building Materials, 2019. 209: p. 619–630. [View at Google Scholar]

[20] Chan, S., et al., Pavement preservation: A solution for sustainability. Transportation research record, 2011. 2235(1): p. 36–42. [View at Google Scholar]

[21] Mohammed, M.S., H. ElKady, and H.A. Abdel-Gawwad, Utilization of construction and demolition waste and synthetic aggregates. Journal of Building Engineering, 2021. 43: p. 103207. [View at Google Scholar]

[22] Nodehi, M. and V. Mohamad Taghvaee, Sustainable concrete for circular economy: a review on use of waste glass. Glass Structures & Engineering, 2022. 7(1): p. 3–22. [View at Google Scholar]

[23] Nodehi, M. and F. Aguayo, Ultra high performance and high strength geopolymer concrete. Journal of Building Pathology and Rehabilitation, 2021. 6(1): p. 34. [View at Google Scholar]

[24] Nodehi, M., A comparative review on foam-based versus lightweight aggregate-based alkali-activated materials and geopolymer. Innovative Infrastructure Solutions, 2021. 6(4): p. 231. [View at Google Scholar]

[25] Barbhuiya, S., T. Qureshi, and B.B. Das, Advancing sustainable pavements: a review of low-carbon construction materials and practices. Discover Concrete and Cement, 2025. 1(1): p. 19. [View at Google Scholar]

[26] Wu, J., X. Ye, and H. Cui, Recycled Materials in Construction: Trends, Status, and Future of Research. Sustainability, 2025. 17(6): p. 2636. [View at Google Scholar]

[27] Shi, X., A. Mukhopadhyay, and D. Zollinger, Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates. Journal of Cleaner Production, 2018. 192: p. 569–581. [View at Google Scholar]

[28] Piao, Z., et al., Urban mining for asphalt pavements: A review. Journal of Cleaner Production, 2021. 280: p. 124916. [View at Google Scholar]

[29] Safiuddin, M., et al., Use of recycled concrete aggregate in concrete: a review. Journal of civil engineering and management, 2013. 19(6): p. 796–810. [View at Google Scholar]

[30] Brand, A.S. and J.R. Roesler, Bonding in cementitious materials with asphalt-coated particles: Part I–The interfacial transition zone. Construction and Building Materials, 2017. 130: p. 171–181. [View at Google Scholar]

[31] Brand, A.S. and J.R. Roesler, Bonding in cementitious materials with asphalt-coated particles: Part II–Cement-asphalt chemical interactions. Construction and Building Materials, 2017. 130: p. 182–192. [View at Google Scholar]

[32] Singh, S., K. Monu, and G. Ransinchung Rn, Laboratory investigation of RAP for various layers of flexible and concrete pavement. International Journal of Pavement Engineering, 2020. 21(14): p. 1780–1793. [View at Google Scholar]

[33] Shi, X., et al., Characterization of two-parameter fracture properties of portland cement concrete containing reclaimed asphalt pavement aggregates by semicircular bending specimens. Cement and Concrete Composites, 2019. 95: p. 56–69. [View at Google Scholar]

[34] Fakhri, M. and E. Amoosoltani, The effect of reclaimed asphalt pavement and crumb rubber on mechanical properties of roller compacted concrete pavement. Construction and Building Materials, 2017. 137: p. 470–484. [View at Google Scholar]

[35] Khakbaz, M., et al., A review of the application of fracture mechanics in investigating the behavior of flexible and rigid pavements. Road, 2024. 32(121): p. 115–136. [View at Google Scholar]

[36] Fakhri, M., et al., Determining optimal combination of roller compacted concrete pavement mixture containing recycled asphalt pavement and crumb rubber using hybrid artificial neural network–genetic algorithm method considering energy absorbency approach. Canadian Journal of Civil Engineering, 2017. 44(11): p. 945–955. [View at Google Scholar]

[37] Fakhri, M., E. Amoosoltani, and M. Aliha, Crack behavior analysis of roller compacted concrete mixtures containing reclaimed asphalt pavement and crumb rubber. Engineering Fracture Mechanics, 2017. 180: p. 43–59. [View at Google Scholar]

[38] Rooholamini, H., et al., Effect of electric arc furnace steel slag on the mechanical and fracture properties of roller-compacted concrete. Construction and building materials, 2019. 211: p. 88–98. [View at Google Scholar]

[39] Selvam, M., et al., Utilization of alternative aggregates for roller compacted concrete pavements–A state-of-the-art review. Construction and building materials, 2022. 317: p. 125838. [View at Google Scholar]

[40] Hashemi, M., Engineering Characteristics of Modified Rollercompacted Concrete Pavement. 2019, University of Malaya (Malaysia). [View at Google Scholar]

[41] Ahmed, A., et al., Chemical reactions in pozzolanic concrete. Mod. Approaches Mater. Sci, 2019. 1(4): p. 128–133. [View at Google Scholar]

[42] Selvam, M. and S. Singh, Material selection and mixture proportioning methods for sustainable roller-compacted concrete pavements. Journal of Materials in Civil Engineering, 2022. 34(11): p. 03122002. [View at Google Scholar]

[43] Aghayan, I., R. Khafajeh, and M. Shamsaei, Life cycle assessment, mechanical properties, and durability of roller compacted concrete pavement containing recycled waste materials. International Journal of Pavement Research and Technology, 2021. 14(5): p. 595–606. [View at Google Scholar]

[44] Tu, T.-Y., Y.-Y. Chen, and C.-L. Hwang, Properties of HPC with recycled aggregates. Cement and concrete research, 2006. 36(5): p. 943–950. [View at Google Scholar]

[45] Lopez-Uceda, A., et al., Feasibility study of roller compacted concrete with recycled aggregates as base layer for light-traffic roads.

Road Materials and Pavement Design, 2020. 21(1): p. 276–288. [View at Google Scholar]

[46] Dubey, P., et al., Assessing the effect of reclaimed asphalt pavement on mechanical properties of dry-lean concrete. Journal of materials in civil engineering, 2020. 32(11): p. 04020348. [View at Google Scholar]

[47] Singh, S., G. Ransinchung RN, and P. Kumar, Laboratory investigation of concrete pavements containing fine RAP aggregates. Journal of Materials in Civil Engineering, 2018. 30(2): p. 04017279. [View at Google Scholar]

[48] Srivastava, A. Feasibility Study on Use of Washed-Reclaimed Asphalt as a Partial Replacement of Natural Aggregate in Dry-Lean Concrete as Base Course for Rigid Pavement. 2020. ASCE. [View at Google Scholar]

[49] Abu-Eishah, S.I., A.S. El-Dieb, and M.S. Bedir, Performance of concrete mixtures made with electric arc furnace (EAF) steel slag aggregate produced in the Arabian Gulf region. Construction and Building Materials, 2012. 34: p. 249–256. [View at Google Scholar]

[50] Palankar, N., A.R. Shankar, and B. Mithun, Durability studies on eco-friendly concrete mixes incorporating steel slag as coarse aggregates. Journal of cleaner production, 2016. 129: p. 437–448. [View at Google Scholar]

[51] Courard, L., F. Michel, and P. Delhez, Use of concrete road recycled aggregates for roller compacted concrete. Construction and building Materials, 2010. 24(3): p. 390–395. [View at Google Scholar]

[52] Tailby, J. and K.J. MacKenzie, Structure and mechanical properties of aluminosilicate geopolymer composites with Portland cement and its constituent minerals. Cement and Concrete Research, 2010. 40(5): p. 787–794. [View at Google Scholar]

[53] Ayub, M., et al., Promoting sustainable cleaner production paradigms in palm oil fuel ash as an eco-friendly cementitious material: a critical analysis. Journal of Cleaner Production, 2021. 295: p. 126296. [View at Google Scholar]

[54] BAV, R.K. and R. G, Performance evaluation of sustainable materials in roller compacted concrete pavements: A state of art review. Journal of Building Pathology and Rehabilitation, 2022. 7(1): p. 78. [View at Google Scholar]

[55] Hassanshahi, O., et al., Experimental Investigation of Sustainable Roller-Compacted Concrete Pavement (RCCP) Reinforced with Natural Fibers: Mechanical Performance, Durability, and Environmental Impacts. International Journal of Pavement Research and Technology, 2025: p. 1–24. [View at Google Scholar]

[56] Al-Ani, A. and Z.K. Abbas, Strength Evaluation of Roller-Compacted Concrete using Waste Clay-Brick as Aggregate. Engineering, Technology & Applied Science Research, 2025. 15(3): p. 23950–23955. [View at Google Scholar]

[57] Debieb, F., et al., Roller compacted concrete with contaminated recycled aggregates. Construction and Building Materials, 2009. 23(11): p. 3382–3387. [View at Google Scholar]

[58] Lopez-Uceda, A., et al., Mechanical performance of roller compacted concrete with recycled concrete aggregates. Road Materials and Pavement Design, 2018. 19(1): p. 36–55. [View at Google Scholar]

[59] Fardin, H.E. and A.G.d. Santos, Roller compacted concrete with recycled concrete aggregate for paving bases. Sustainability, 2020. 12(8): p. 3154. [View at Google Scholar]

[60] Shamsaei, M., I. Aghayan, and K.A. Kazemi, Experimental investigation of using cross-linked polyethylene waste as aggregate in roller compacted concrete pavement. Journal of cleaner production, 2017. 165: p. 290–297. [View at Google Scholar]

[61] Boussetta, I., S. El Euch Khay, and J. Neji, Experimental testing and modelling of roller compacted concrete incorporating RAP waste as aggregates. European Journal of Environmental and Civil Engineering, 2020. 24(11): p. 1729–1743. [View at Google Scholar]

[62] Williams, S.G., Comparison of the superpave gyratory and proctor compaction methods for the design of roller-compacted concrete pavements. Transportation research record, 2013. 2342(1): p. 106–112. [View at Google Scholar]

[63] Sengun, E., et al., A new evaluation of the fatigue design criteria of roller compacted concrete (RCC) pavements. Construction and building materials, 2021. 289: p. 123195. [View at Google Scholar]

[64] Şengün, E., et al., The effects of compaction methods and mix parameters on the properties of roller compacted concrete mixtures. Construction and Building Materials, 2019. 228: p. 116807. [View at Google Scholar]

[65] LaHucik, J. and J. Roesler, Field and laboratory properties of roller-compacted concrete pavements. Transportation Research Record, 2017. 2630(1): p. 33–40. [View at Google Scholar]

[66] Ashteyat, A., et al., Production of roller compacted concrete made of recycled asphalt pavement aggregate and recycled concrete aggregate and silica fume. International journal of pavement research and technology, 2022. 15(4): p. 987–1002. [View at Google Scholar]

[67] Lam, M.N.-T., S. Jaritngam, and D.-H. Le, Roller-compacted concrete pavement made of Electric Arc Furnace slag aggregate: Mix design and mechanical properties. Construction and building materials, 2017. 154: p. 482–495. [View at Google Scholar]

[68] Settari, C., et al., Assessing the effects of recycled asphalt pavement materials on the performance of roller compacted concrete. Construction and building materials, 2015. 101: p. 617–621. [View at Google Scholar]

[69] Debbarma, S. and G. Ransinchung, Achieving sustainability in roller compacted concrete pavement mixes using reclaimed asphalt pavement aggregates–state of the art review. Journal of Cleaner Production, 2021. 287: p. 125078. [View at Google Scholar]

[70] Ferrebee, E.C., et al., Fracture properties of roller-compacted concrete with virgin and recycled aggregates. Transportation Research Record, 2014. 2441(1): p. 128–134. [View at Google Scholar]

[71] Debbarma, S., S. Singh, and G.R. RN, Laboratory investigation on the fresh, mechanical, and durability properties of roller compacted concrete pavement containing reclaimed asphalt pavement aggregates. Transportation Research Record, 2019. 2673(10): p. 652–662. [View at Google Scholar]

[72] Debbarma, S., et al., Utilization of industrial and agricultural wastes for productions of sustainable roller compacted concrete pavement mixes containing reclaimed asphalt pavement aggregates. Resources, Conservation and Recycling, 2020. 152: p. 104504. [View at Google Scholar]

[73] Zheng, W., et al., Optimization of concrete mix design based on three-level separation distance of particles. Journal of Building Engineering, 2023. 70: p. 106479. [View at Google Scholar]

[74] Keleş, Ö.F., O.Ü. Bayrak, and H.F. Bayata, Experimental investigation on mechanical properties of sustainable roller compacted concrete pavement (RCCP) containing waste rubbers as alternative aggregates. Construction and Building Materials, 2024. 424: p. 135930. [View at Google Scholar]

[75] Debbarma, S., G. Ransinchung, and S. Singh, Feasibility of roller compacted concrete pavement containing different fractions of reclaimed asphalt pavement. Construction and Building Materials, 2019. 199: p. 508–525. [View at Google Scholar]

[76] Adamu, M., B.S. Mohammed, and M.S. Liew, Mechanical properties and performance of high volume fly ash roller compacted concrete containing crumb rubber and nano silica. Construction and Building Materials, 2018. 171: p. 521–538. [View at Google Scholar]

[77] Modarres, A. and Z. Hosseini, Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material. Materials & Design, 2014. 64: p. 227–236. [View at Google Scholar]

[78] Mardani-Aghabaglou, A. and K. Ramyar, Mechanical properties of high-volume fly ash roller compacted concrete designed by maximum density method. Construction and building materials, 2013. 38: p. 356–364. [View at Google Scholar]

[79] Tavakoli, D., P. Fakharian, and J. de Brito, Mechanical properties of roller-compacted concrete pavement containing recycled brick aggregates and silica fume. Road Materials and Pavement Design, 2022. 23(8): p. 1793–1814. [View at Google Scholar]

[80] Aghaeipour, A. and M. Madhkhan, Effect of ground granulated blast furnace slag (GGBFS) on RCCP durability. Construction and

Building Materials, 2017. 141: p. 533–541. [View at Google Scholar]

[81] Chhorn, C., S.J. Hong, and S.W. Lee, Relationship between compressive and tensile strengths of roller-compacted concrete. Journal of Traffic and Transportation Engineering (English Edition), 2018. 5(3): p. 215–223. [View at Google Scholar]

[82] Hosseinnezhad, H., D. Hatungimana, and K. Ramyar, Mechanical properties of roller compacted concrete containing recycled concrete aggregate. Revista de la construcción, 2021. 20(2): p. 277–290. [View at Google Scholar]

[83] Meddah, A., M. Beddar, and A. Bali, Use of shredded rubber tire aggregates for roller compacted concrete pavement. Journal of Cleaner Production, 2014. 72: p. 187–192. [View at Google Scholar]

[84] Toffolo, R., et al., Roller-compacted concrete pavements produced entirely with steelmaking slag aggregates. ACI Materials Journal, 2021. 118(4): p. 51–64. [View at Google Scholar]

[85] Dong, Q., et al., Recycling of steel slag aggregate in portland cement concrete: An overview. Journal of cleaner production, 2021. 282: p. 124447. [View at Google Scholar]

[86] Lam, M.N.-T., D.-H. Le, and S. Jaritngam, Compressive strength and durability properties of roller-compacted concrete pavement containing electric arc furnace slag aggregate and fly ash. Construction and building materials, 2018. 191: p. 912–922. [View at Google Scholar]

[87] Rao, S.K., P. Sravana, and T.C. Rao, Abrasion resistance and mechanical properties of Roller Compacted Concrete with GGBS. Construction and building materials, 2016. 114: p. 925–933. [View at Google Scholar]

[88] Atiş, C., et al., Strength properties of roller compacted concrete containing a non-standard high calcium fly ash. Materials Letters, 2004. 58(9): p. 1446–1450. [View at Google Scholar]

[89] Aitcin, P.-C. and A. Neville, How the water-cement ratio affects concrete strength. Concrete International, 2003. 25(8). [View at Google Scholar]

[90] Vahedifard, F., M. Nili, and C.L. Meehan, Assessing the effects of supplementary cementitious materials on the performance of low-cement roller compacted concrete pavement. Construction and Building Materials, 2010. 24(12): p. 2528–2535. [View at Google Scholar]

[91] Fakhri, M., The effect of waste rubber particles and silica fume on the mechanical properties of roller compacted concrete pavement. Journal of cleaner production, 2016. 129: p. 521–530. [View at Google Scholar]

[92] Özbay, E., M. Erdemir, and H.İ. Durmuş, Utilization and efficiency of ground granulated blast furnace slag on concrete properties–A review. Construction and Building Materials, 2016. 105: p. 423–434. [View at Google Scholar]

[93] Khankhaje, E., et al., A review of utilization of industrial waste materials as cement replacement in pervious concrete: An alternative approach to sustainable pervious concrete production. Heliyon, 2024. 10(4). [View at Google Scholar]

[94] Tavakoli, D., et al., Properties of roller-compacted concrete pavement containing waste aggregates and nano SiO2. Construction and Building Materials, 2020. 249: p. 118747. [View at Google Scholar]